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[54] **PRE-CODING METHOD AND APPARATUS FOR MULTIPLE SOURCE OR TIME-SHIFTED SINGLE SOURCE DATA AND CORRESPONDING INVERSE POST-DECODING METHOD AND APPARATUS**

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[51] Int. Cl.^{6} **G06K 9/36**
[52] U.S. Cl. **382/232**; 382/236
[58] Field of Search 382/232, 233, 382/236, 238; 358/430; 348/409, 415, 438; 341/76

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,602,333	7/1986	Komori	364/414
5,177,796	1/1993	Feig et al.	382/56
5,448,642	9/1995	Yeh	382/232

FOREIGN PATENT DOCUMENTS

60-186971	9/1985	Japan	382/236

OTHER PUBLICATIONS

English Translation of Japanese Kokai 60–186971 to Izumi et al., Sep. 1985.
"Tag Image File Format, Specification, Revision 5.0," Aldus/Microsoft Technical Memorandum, Aug. 8, 1988, pp. F–7 and F–8.

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[57] **ABSTRACT**

A pre-coding method and device for improving data compression performance by removing correlation between a first original data set and a second original data set, each having M members, respectively. The pre-coding method produces a compression-efficiency-enhancing double-difference data set. The method and device produce a double-difference data set, i.e., an adjacent-delta calculation performed on a cross-delta data set or a cross-delta calculation performed on two adjacent-delta data sets, from either one of (1) two adjacent spectral bands coming from two discrete sources, respectively, or (2) two time-shifted data sets coming from a single source. The resulting double-difference data set is then coded using either a distortionless data encoding scheme (entropy encoding) or a lossy data compression scheme. Also, a post-decoding method and device for recovering a second original data set having been represented by such a double-difference data set.

44 Claims, 18 Drawing Sheets

Encoding Scheme
(Adjacent-Cross)

For an N=8 bit word
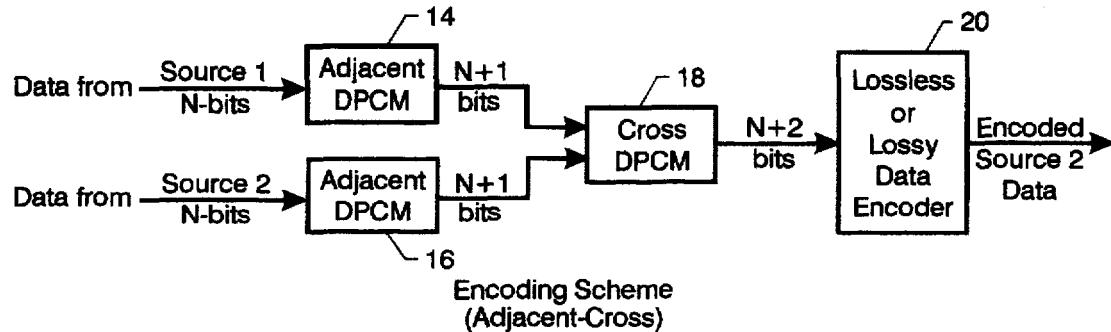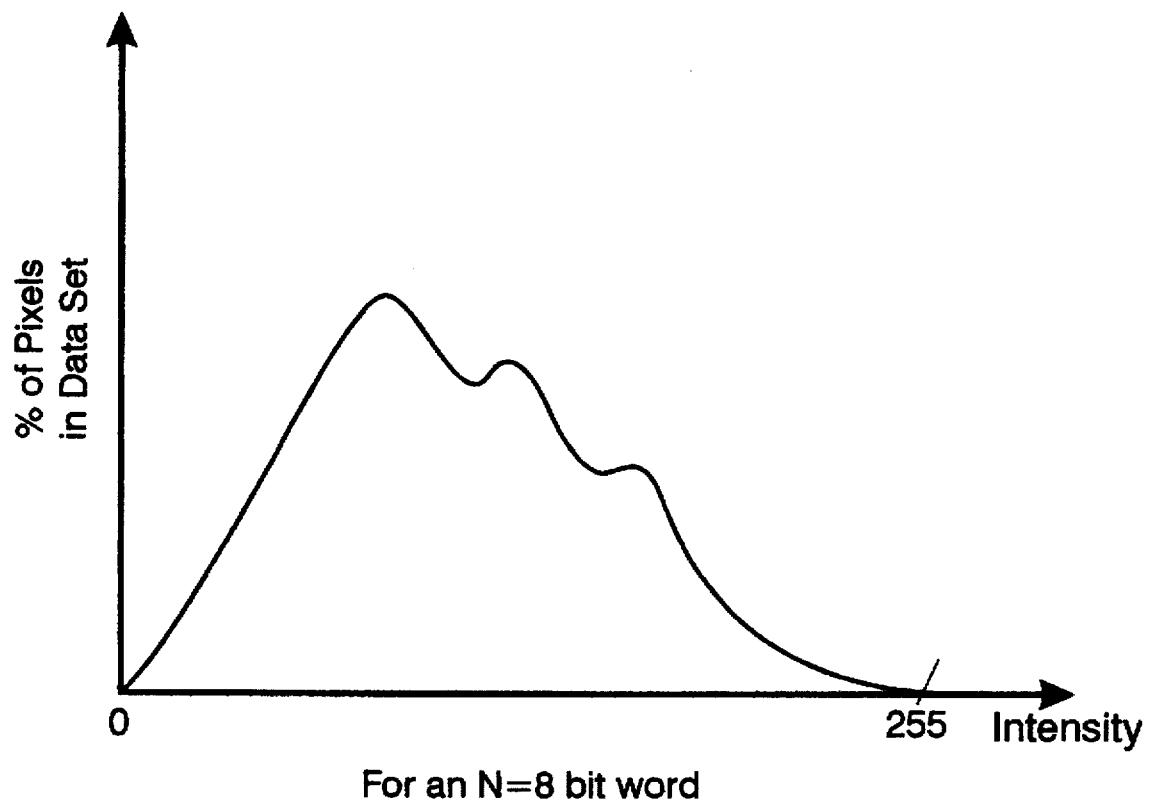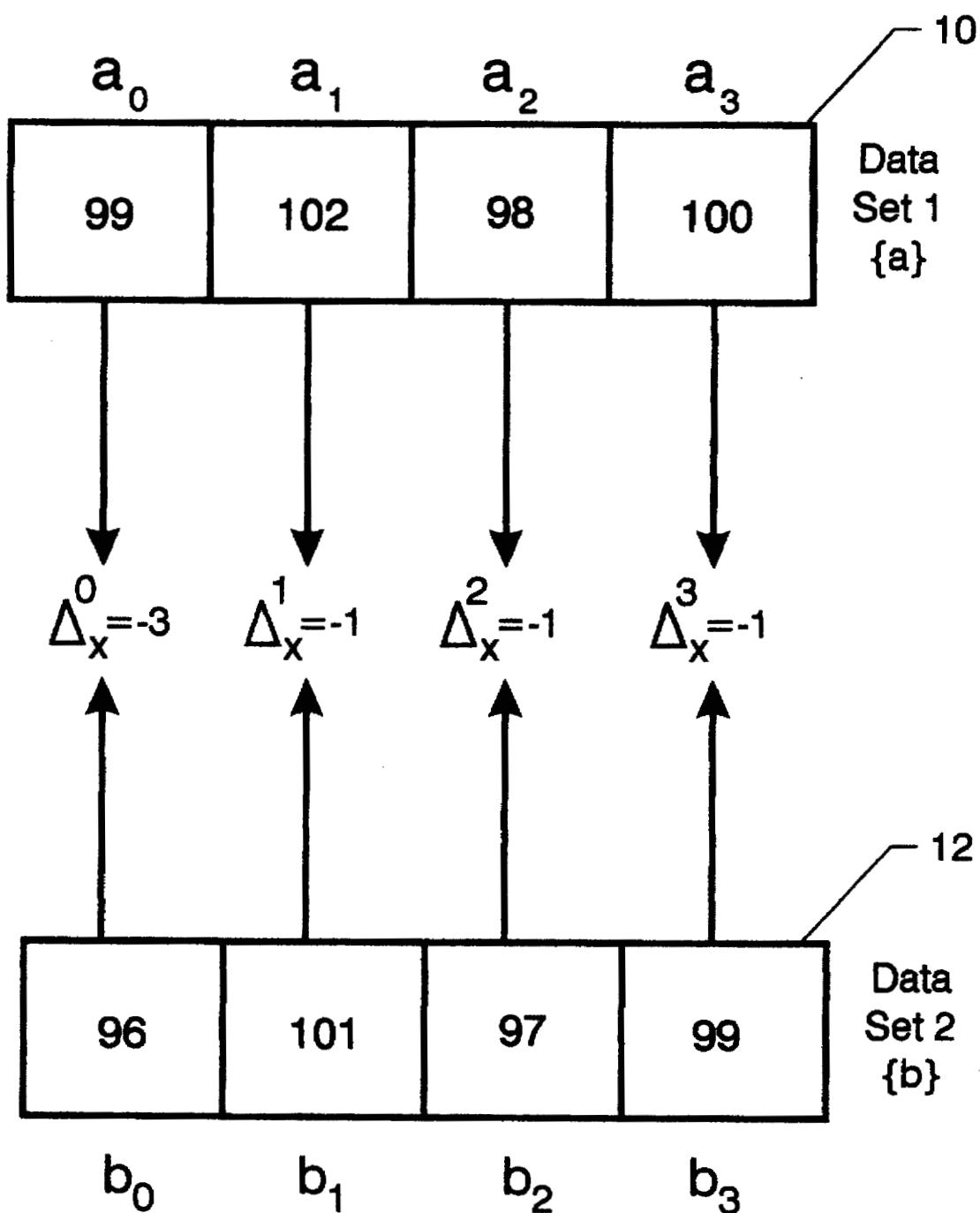
FIG. 1
PRIOR ART

FIG. 2
PRIOR ART
{Cross-Delta Single Difference}
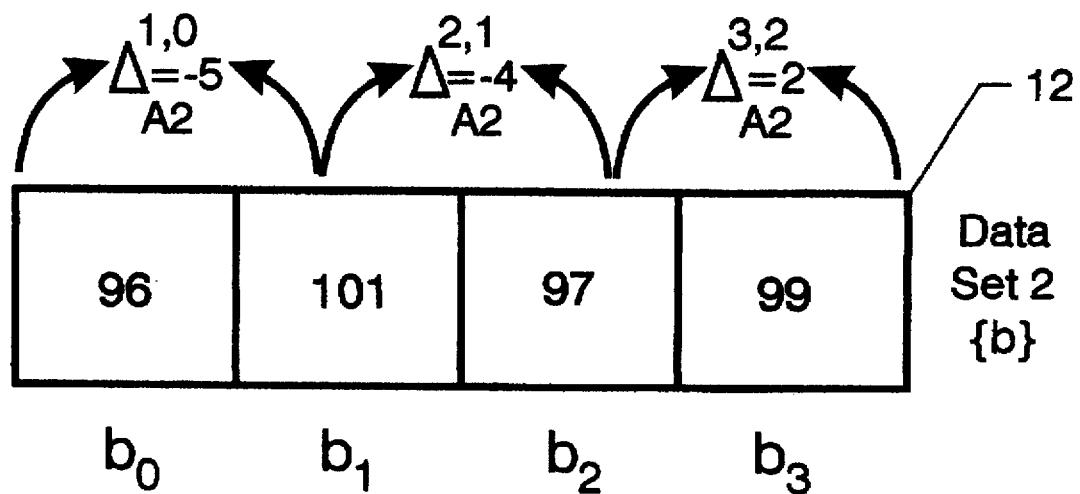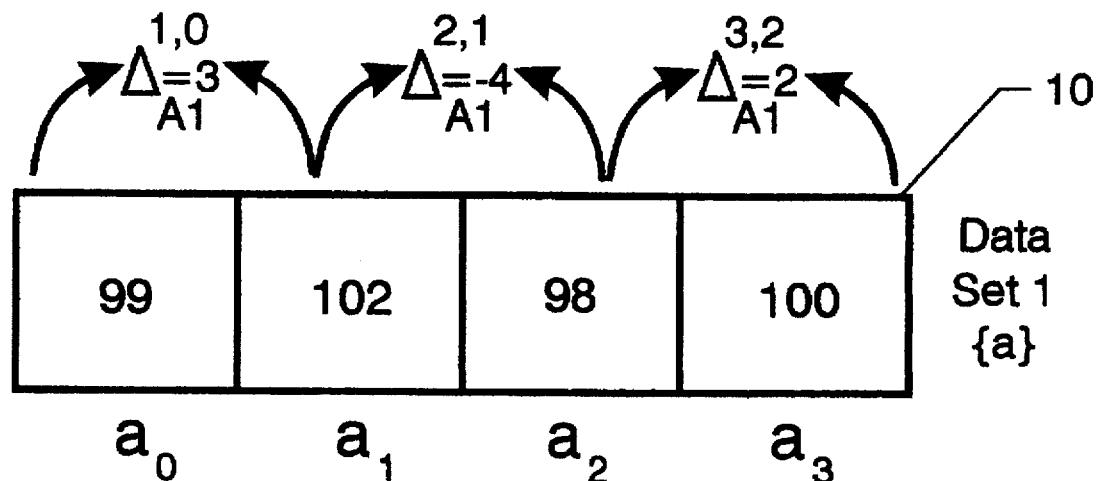
FIG. 3
PRIOR ART
{Adjacent-Delta Single Difference}

FIG. 4

FIG. 5

$$a_0 \qquad a_1 \qquad a_2 \qquad a_3$$

99	102	98	100

Data Set 1 {a} — 10

$$\Delta^{1,0}_{A1}=3 \qquad \Delta^{2,1}_{A1}=-4 \qquad \Delta^{3,2}_{A1}=2$$

$$\Delta^{0}_{X}=2 \qquad \Delta^{1}_{X}=0 \qquad \Delta^{2}_{X}=0 \qquad \left\{\Delta_X\right\}$$

$$\Delta^{1,0}_{A2}=5 \qquad \Delta^{2,1}_{A2}=-4 \qquad \Delta^{3,2}_{A2}=2$$

96	101	97	99

Data Set 2 {b} — 12

$$b_0 \qquad b_1 \qquad b_2 \qquad b_3$$
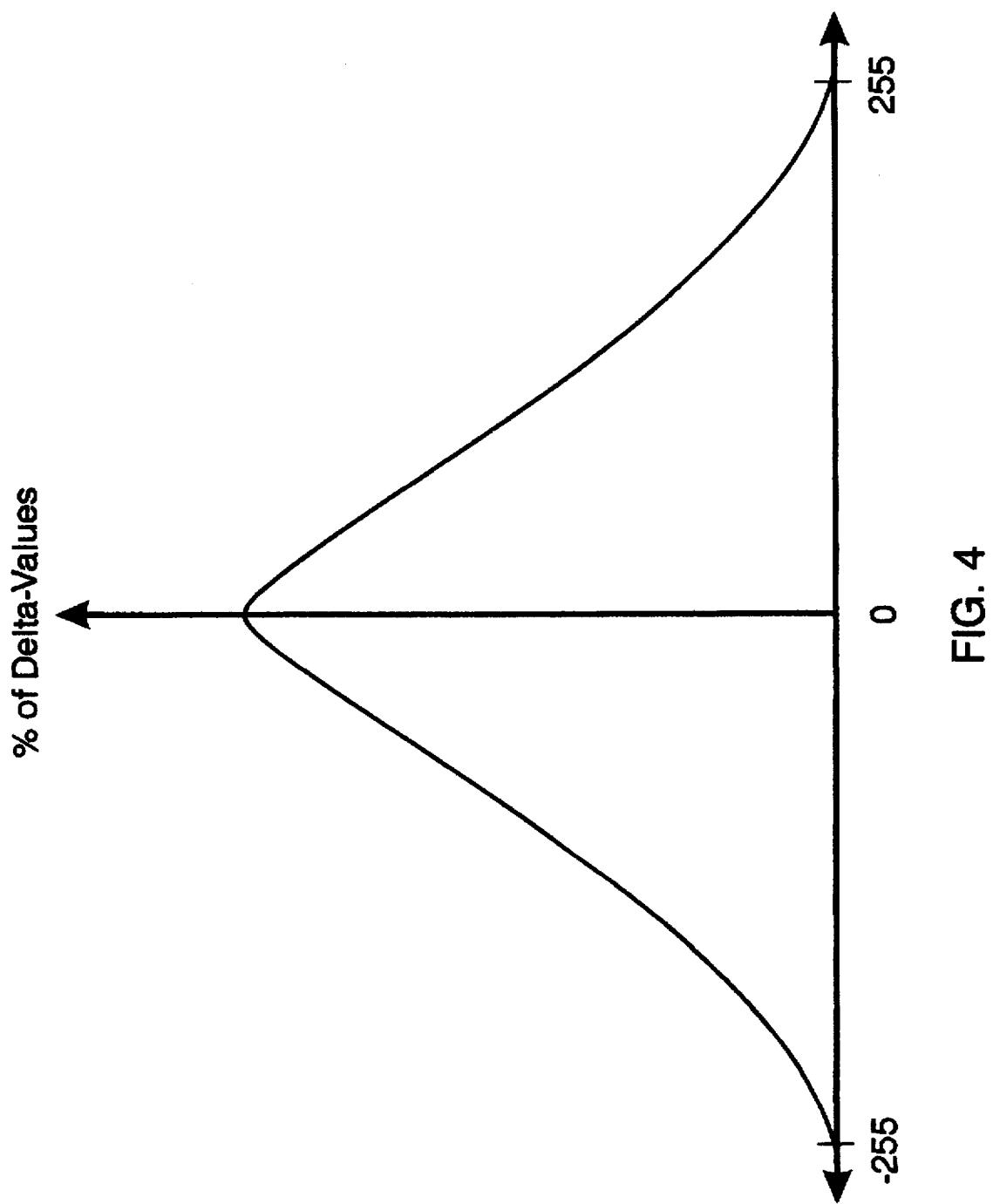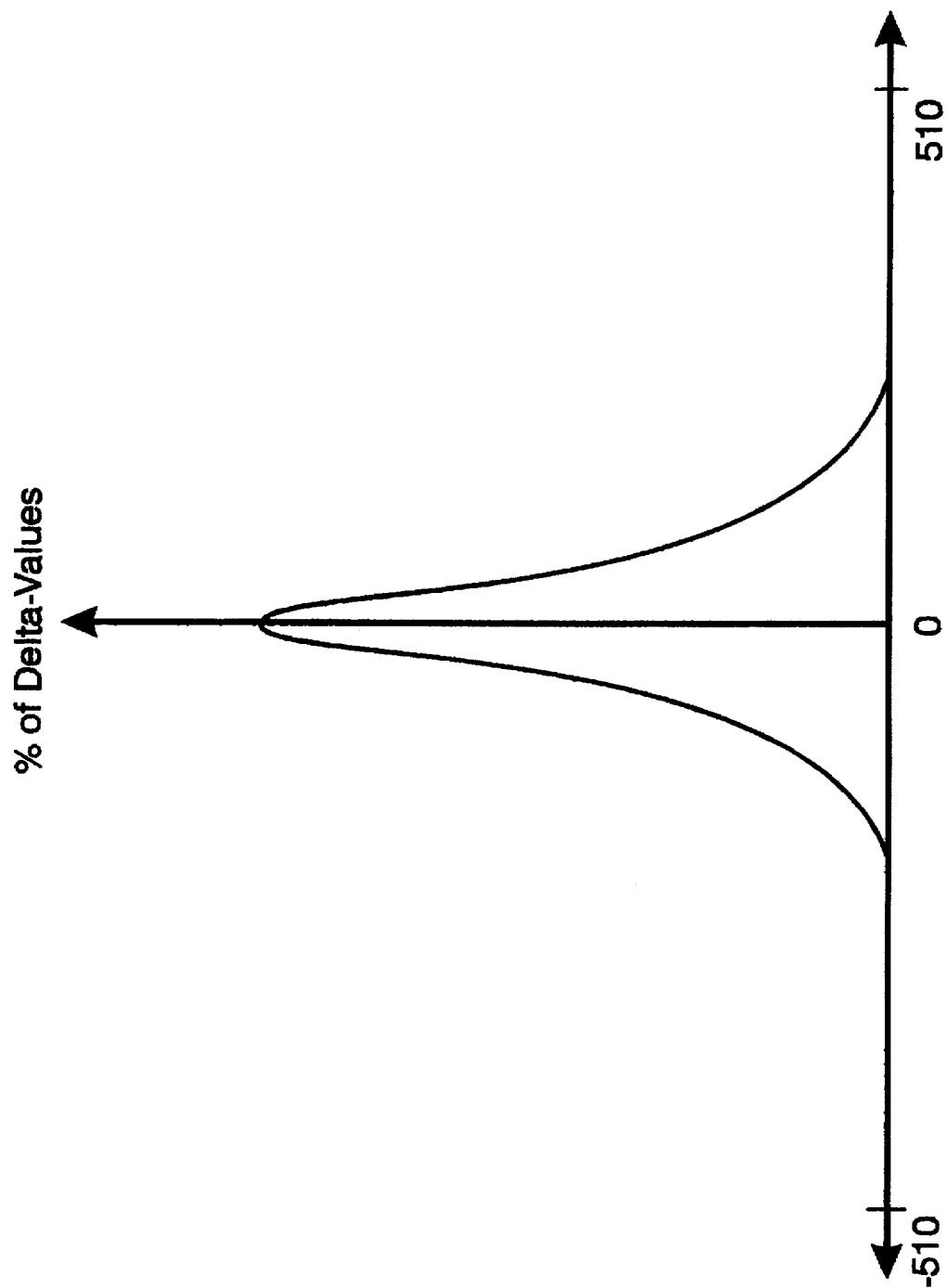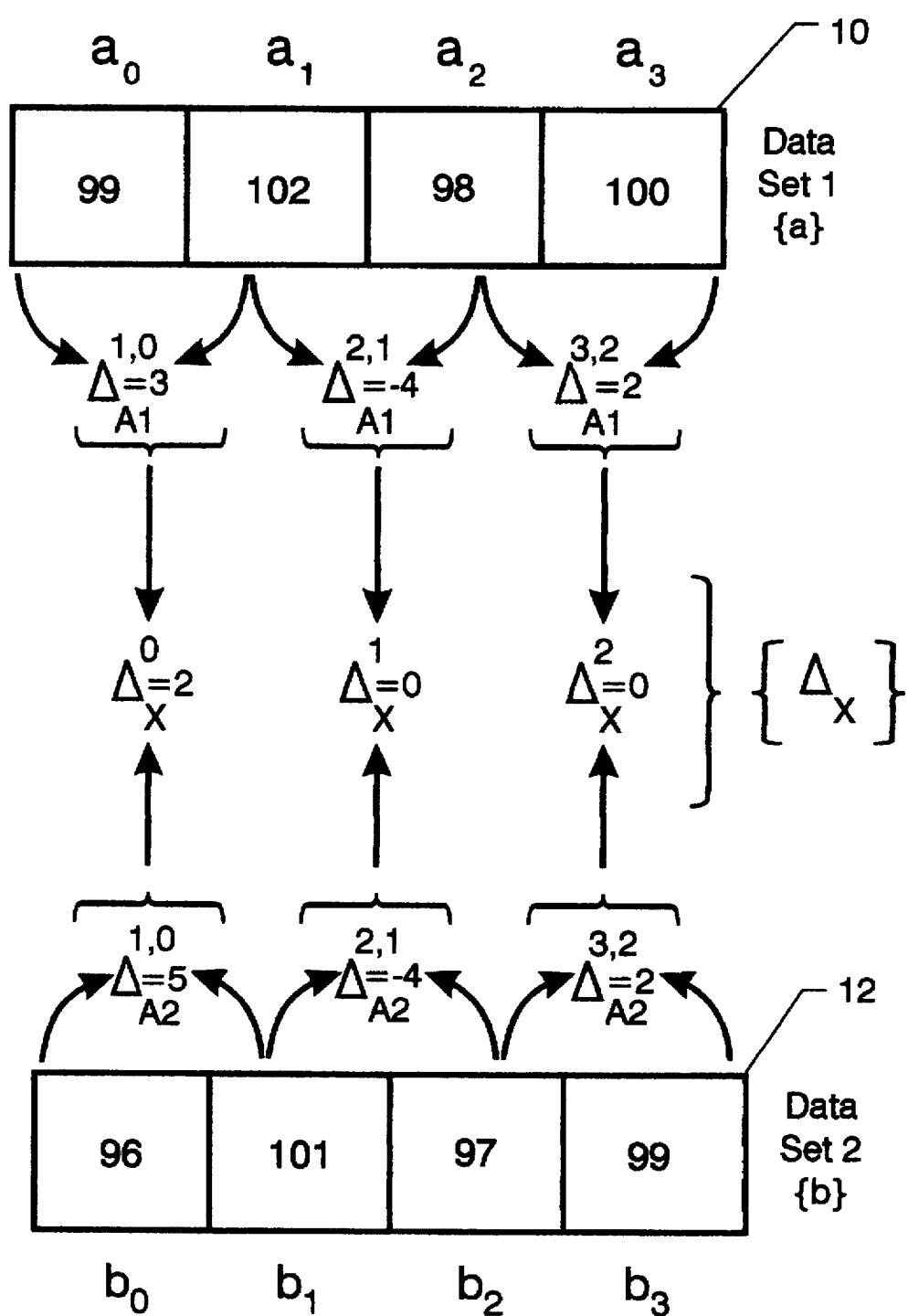
FIG. 6

$$\begin{bmatrix} \text{Double-Difference,} \\ \text{Adjacent + Cross} \end{bmatrix}$$

Either $\left\{ \Delta_{A1} \right\}$ or $\left\{ a \right\}$ is stored

a_0 $\qquad$ a_1 $\qquad$ a_2 $\qquad$ a_3 $\qquad$ — 10

99	102	98	100

Data Set 1 {a}

$\Delta_{A1}^{1,0} = 3$ $\qquad$ $\Delta_{A1}^{2,1} = -4$ $\qquad$ $\Delta_{A1}^{3,2} = 2$ $\qquad$ $\left\{ \Delta_{A1} \right\}$

Stored Double Difference Data

$\Delta_X^0 = 2$ $\qquad$ $\Delta_X^1 = 0$ $\qquad$ $\Delta_X^2 = 0$ $\qquad$ $\left\{ \Delta_X \right\}$

$\Delta_{A2}^{1,0} = 5$ $\qquad$ $\Delta_{A2}^{2,1} = -4$ $\qquad$ $\Delta_{A2}^{3,2} = 2$ $\qquad$ — 12

96	101	97	99

Data Set 2 {b}

b_0 $\qquad$ b_1 $\qquad$ b_2 $\qquad$ b_3 $\qquad$

To be reconstructed (except for b_0)

Stored bit b_0

FIG. 8

$\left[\begin{array}{c} \text{Inverse of} \\ \text{Fig. 6} \end{array} \right]$

Encoding Scheme
(Adjacent-Cross)
FIG. 7

Decoding Scheme
FIG. 9

a_0 a_1 a_2 a_3 — 10

| 99 | 102 | 98 | 100 | Data Set 1 {a} |

$\Delta_A^{1,0}=2$ $\Delta_A^{2,1}=0$ $\Delta_A^{3,2}=0$ $\left\{ \Delta_A \right\}$

$\Delta_X^0=-3$ $\Delta_X^1=-1$ $\Delta_X^2=-1$ $\Delta_X^3=-1$ $\left\{ \Delta_X \right\}$

— 12

| 96 | 101 | 97 | 99 | Data Set 2 {b} |

b_0 b_1 b_2 b_3

FIG. 10

$\left[\begin{array}{c} \text{Double-Difference,} \\ \text{Cross+Adjacent} \end{array} \right]$

Data from Source 1 N-bits → Cross DPCM (30) → N+1 bits → Adjacent DPCM (32) → N+2 bits → Lossless or Lossy Data Encoder (34) → Encoded Source Data

Data from Source 2 N-bits →
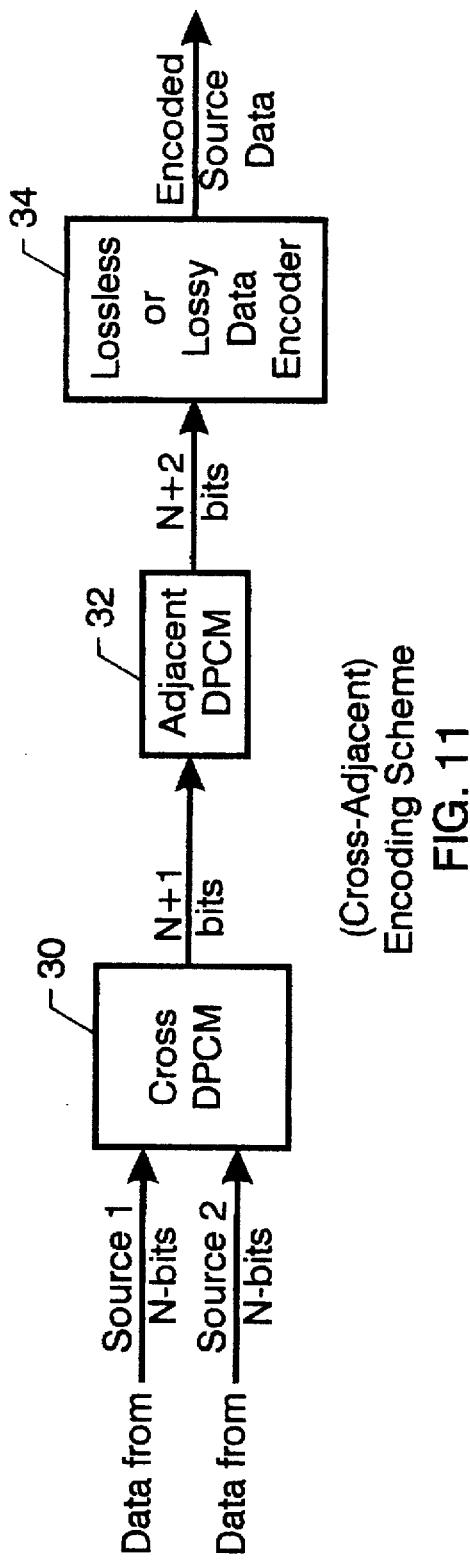
(Cross-Adjacent)
Encoding Scheme
FIG. 11

Data from Source 1 N-bits → (DPCM)⁻¹ (40) → Decoded Source 2 N-bits

Encoded Source 2 → Lossless or Lossy Data Decoder (36) → N+2 bits → (DPCM)⁻¹ (38) → N+1 bits → (DPCM)⁻¹ (40)

Decoding Scheme
FIG. 13

a_0 a_1 a_2 a_3

| 99 | 102 | 98 | 100 |

Stored {a}

Stored Double Difference Data $\left\{ \Delta_A \right\}$

$\Delta_A^{1,0} = 2$ $\Delta_A^{2,1} = 0$ $\Delta_A^{3,2} = 0$

$\Delta_x^0 = -3$ $\Delta_x^1 = -1$ $\Delta_x^2 = -1$ $\Delta_x^3 = -1$

Stored

| 96 | 101 | 97 | 99 |

Data Set 2 {b}

b_0 b_1 b_2 b_3

To be reconstructed (except for b_0)

Stored bit b_0
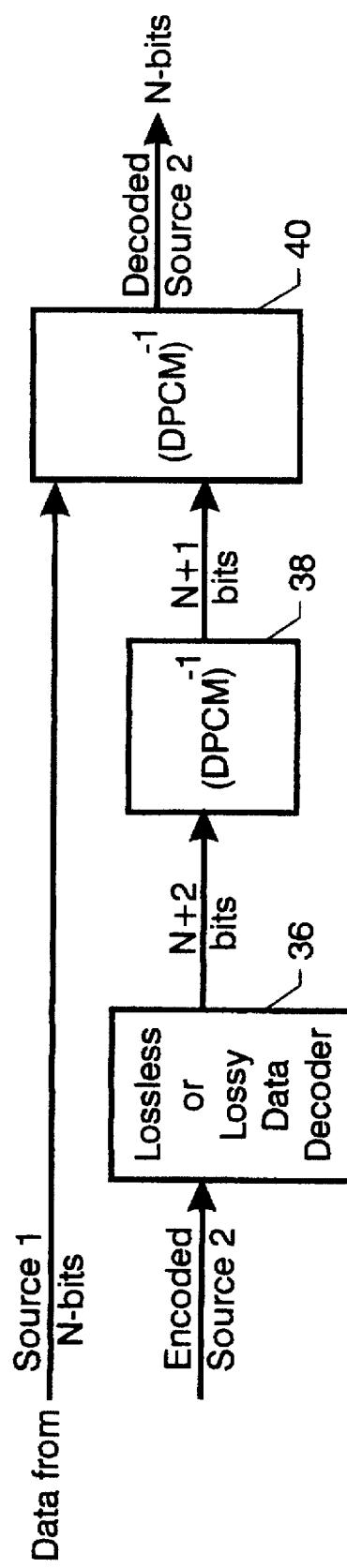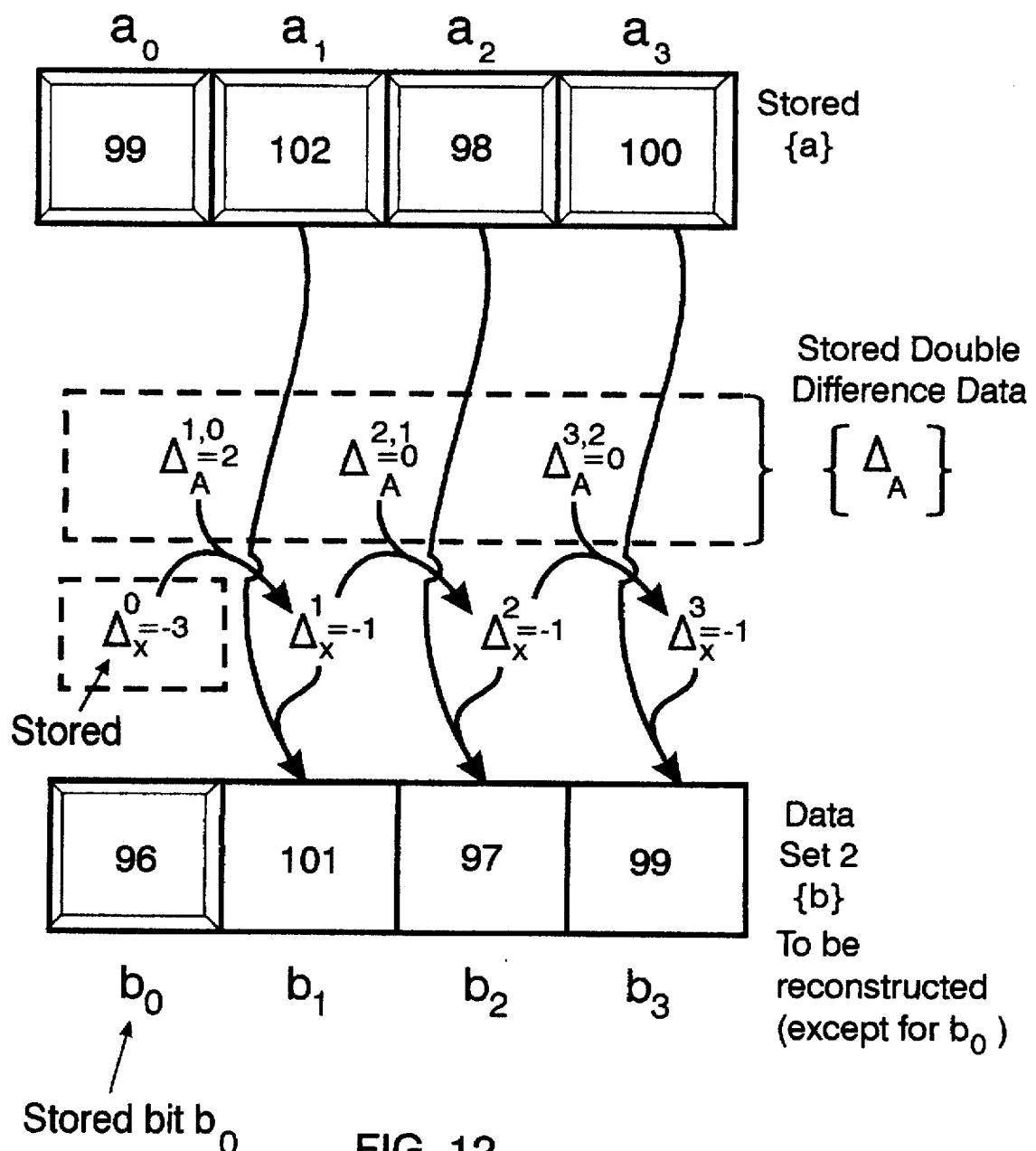
FIG. 12

$\left[\begin{array}{c} \text{Inverse of} \\ \text{Fig. 10} \end{array} \right]$
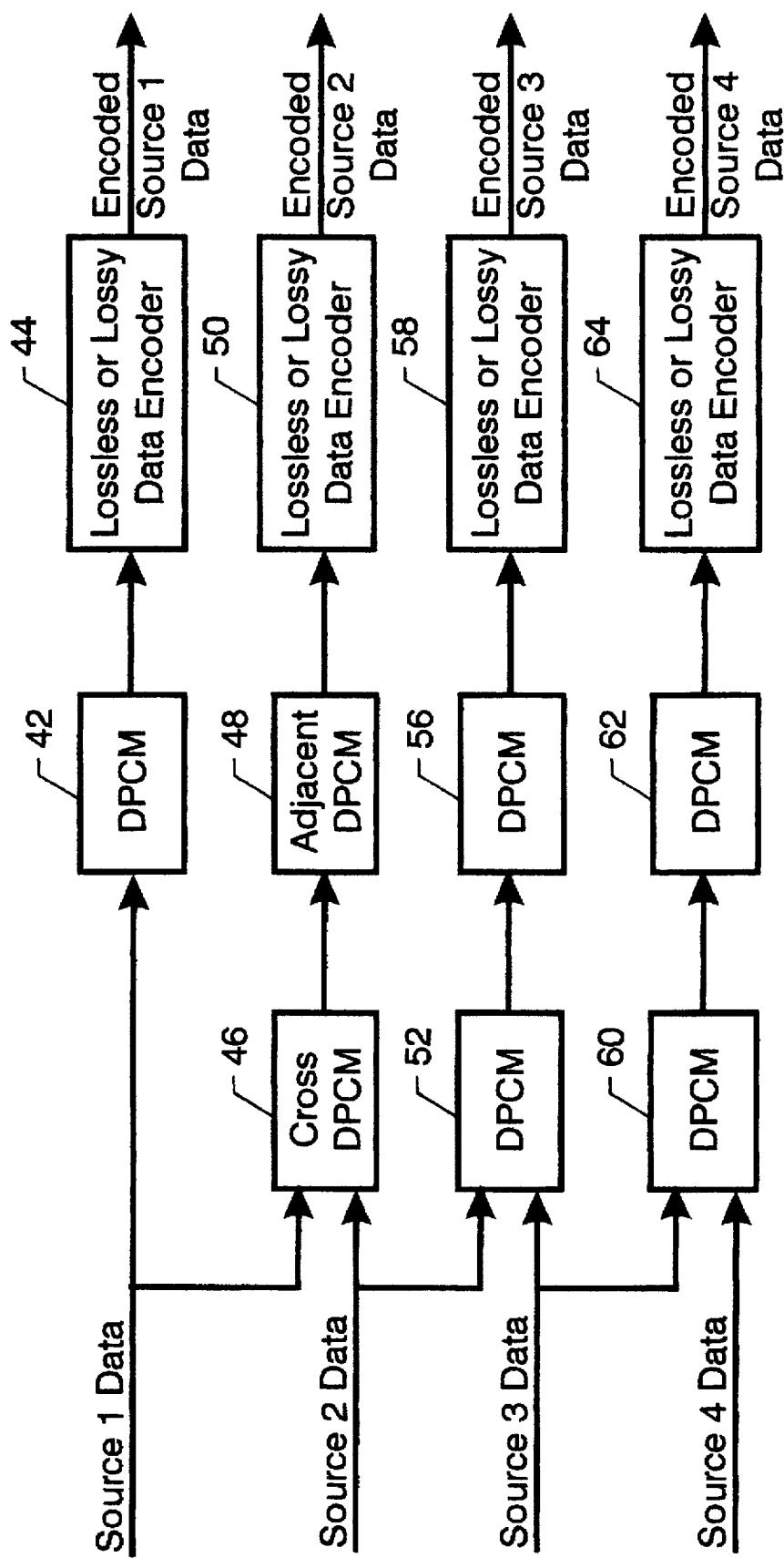
Multi-source Encoder Architecture

FIG. 14
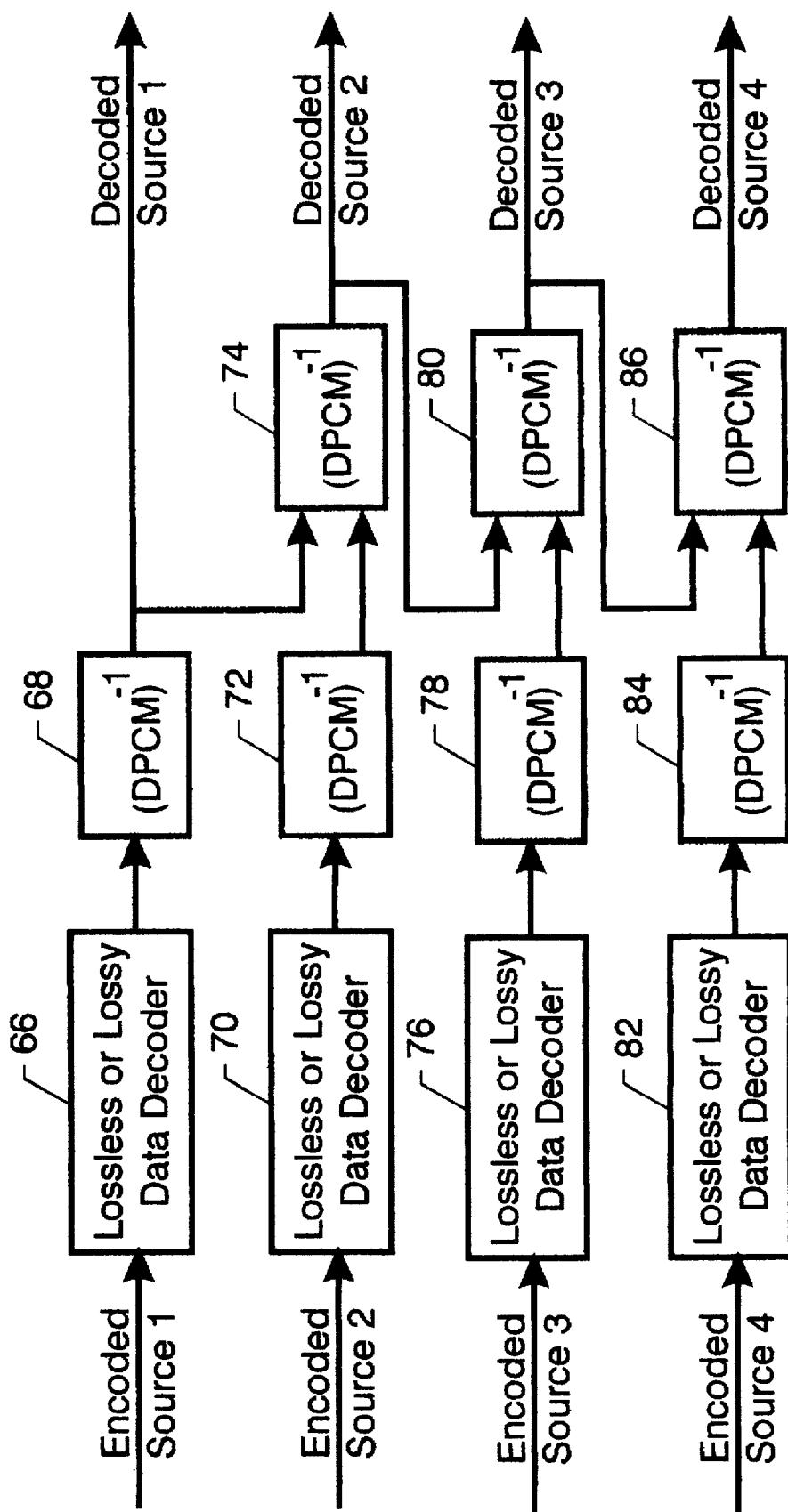
Multi-source Decoder Architecture

FIG. 15
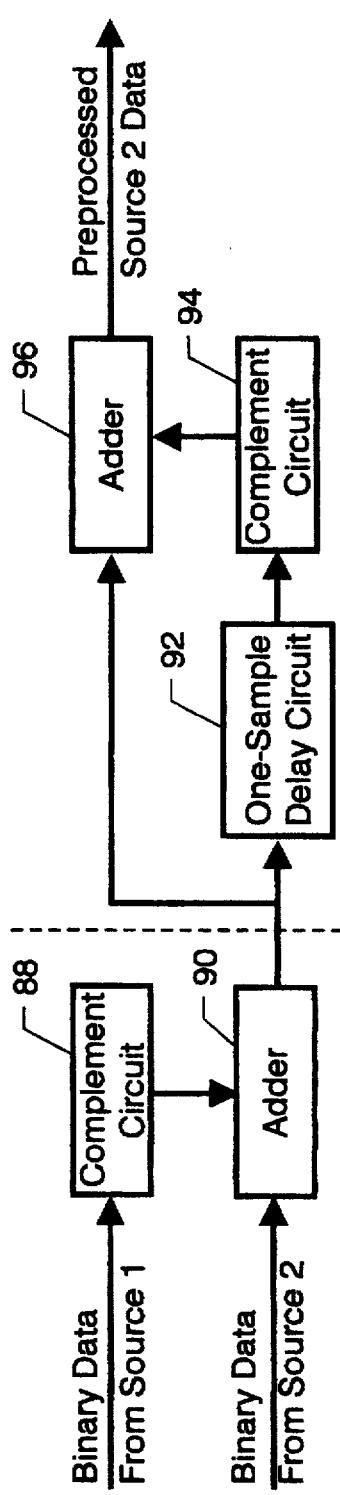
Preferred hardware embodiment for the two DPCM blocks
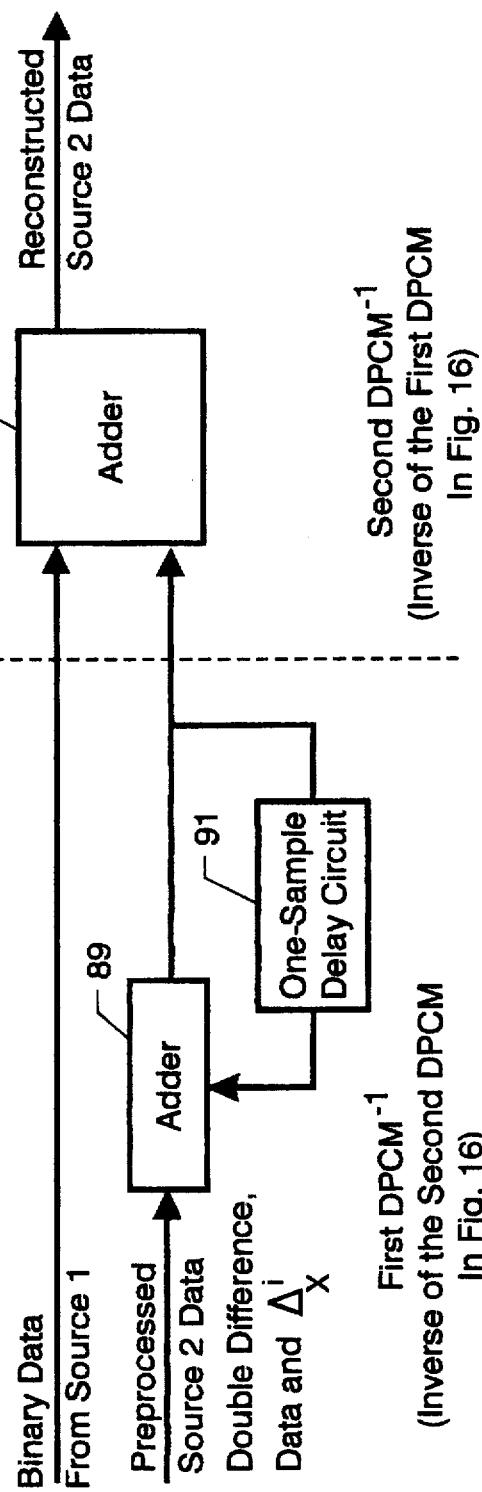
FIG. 16

Preferred hardware embodiment for the two inverse DPCM blocks in the data reconstruction operator

FIG. 17

FIG. 18

FIG. 19

116

First
Data
Source
Memory

120

Second
Data
Source
Memory

118

Programmed
Computer

Double-Difference
Data Set
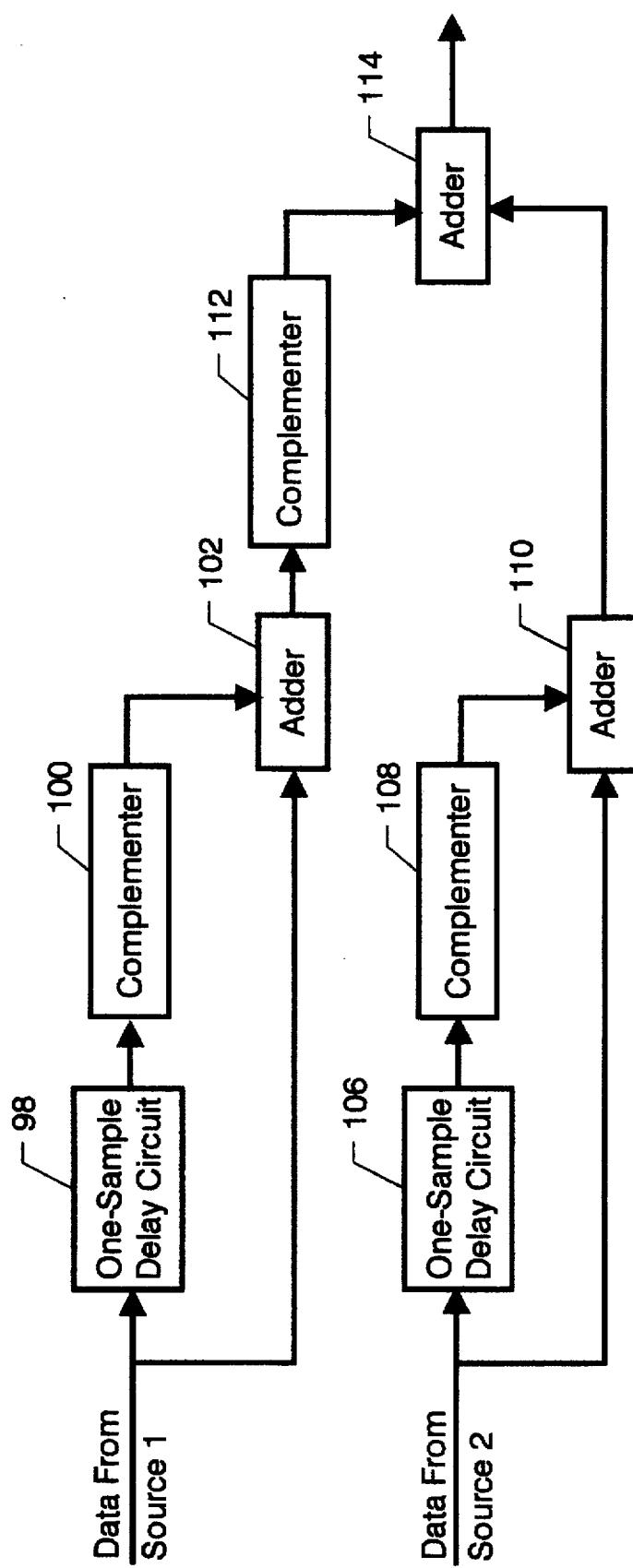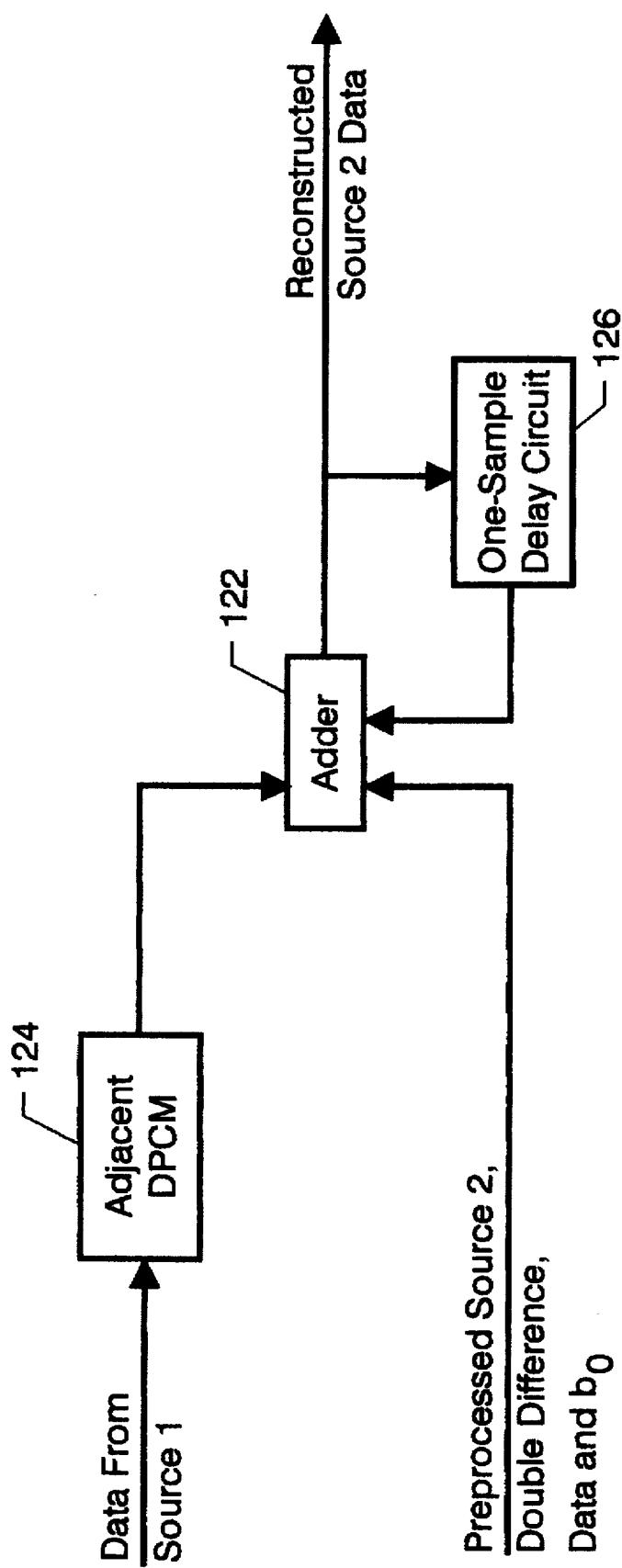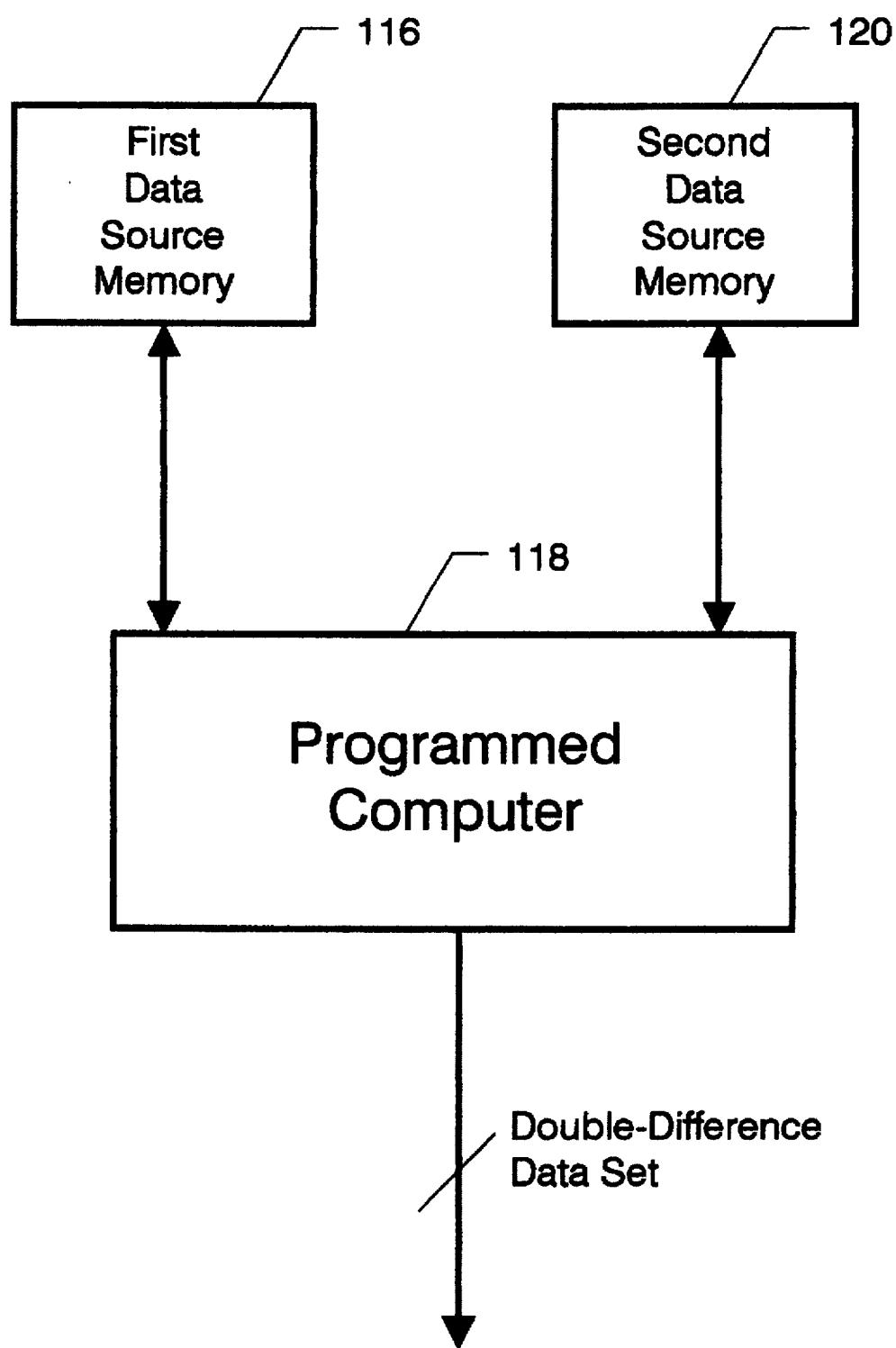
FIG. 20
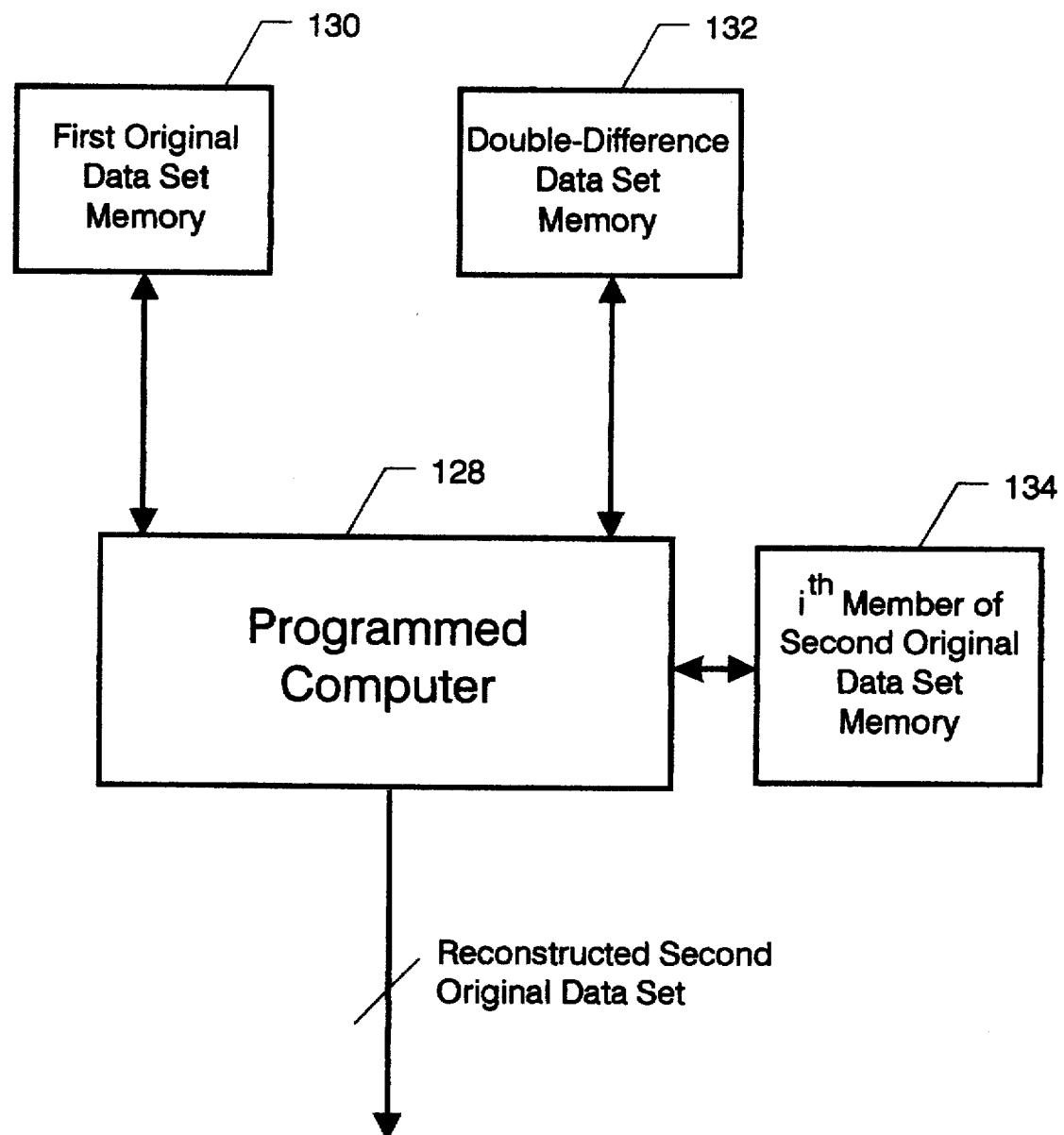
FIG. 21

PRE-CODING METHOD AND APPARATUS FOR MULTIPLE SOURCE OR TIME-SHIFTED SINGLE SOURCE DATA AND CORRESPONDING INVERSE POST-DECODING METHOD AND APPARATUS

ORIGIN OF THE INVENTION

The invention described herein was made by an employee of the United States Government, and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

CROSS-REFERENCES TO RELATED APPLICATIONS

The present application involves subject matter relating to application Ser. No. 08/195,899 filed Feb. 14, 1994, U.S. Pat. No. 5,448,642, which is a continuation of Ser. No. 07/881,575, entitled, "Method for Encoding Low Entropy Data," filed in the name of Pen-Shu Yeh, the present inventor, on May 12, 1992. The above-noted related application is assigned to the assignee of the present invention. Moreover, the teachings of this related application are herein meant to be incorporated by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a pre-compression-coding method that improves data compression performance by removing correlation between a first original data set and a second original data set.

2. Description of the Prior Art

In general, data compression reduces an amount of data to be stored or transmitted by removing the correlation and redundancy in the data and representing efficiently the remaining information with codewords. An optimal compression coding scheme will give an expected codeword length close to the information measure, a figure of merit referred to as entropy, in the original data. An example of such a coding scheme is the Huffman code. In addition, there are encoding schemes that produce expected codeword lengths shorter than the information measure in the original data. Such schemes are referred to as lossy data compression because the reconstructed data will be distorted from the original data. The prior art performs data compression, for the most part, on data obtained from a single source (producing a single spectral band), using either a distortionless or lossy technique.

Advances in sensor technology have allowed new data collection schemes which generate plural data sets simultaneously from multiple sources. Such plural data sets include imaging data from multiple spectral bands, often referred to as multispectral data, and spectral distributions from a radio frequency source sampled at different times, i.e., time-shifted.

An example of multispectral sensor data is the data collected from the Thematic Mapper on the Landsat spacecraft. The Landsat program was initiated for the study of the Earth's surface and resources in the 1970's. Landsat-1, Landsat-2, and Landsat-3 were launched between 1972 and 1978. Landsat-4 was launched in 1982, and Landsat-5 in 1984. The Thematic Mapper on Landsat-4 and -5 collected data in six spectral bands; (1) D. R. Sloggett, *Satellite data: processing, archiving and dissemination, Vol.* 1, *Applications and infrastructure,* published by Ellis Horwood

Limited, distributed by Halsted Press, a division of John Wiley & Sons, 1989, and (2) P. S. Yeh and W. H. Miller, "Application guide for universal source encoding for space," NASA Technical Paper 3441, December 1993. An example of a spectral distribution sampled at different times is the Acousto-Optical Spectrometer ("AOS") on the Submillimeter Wave Astronomy Satellite ("SWAS") which is to be launched in 1995. The AOS sensor collects the radio-frequency spectrum of galactical molecular clouds at different times to observe changes; G. Chin, "Optically pumped submillimeter laser heterodyne receivers: astrophysical observations and recent technical developments," *Proceedings of the IEEE,* Vol. 80, No. 11, November, 1992. Such data is useful to scientific investigation and earth resource monitoring, yet it presents problems in terms of data transmission, processing, and storage because of the large amounts of original data generated.

Modern imaging sensors, whose uses include scientific studies in the areas of astronomy, earth resources, or commercial applications such as high definition TV, typically produce data samples which are quantized into, for example, 8 or 12 bits/sample. As shown in FIG. 1, an 8-bit word can represent 256 pixel intensity values. Typically, the intensities in a set of image data are not evenly distributed, but rather are concentrated in one or a few small ranges.

Such image data can have an actual information content that is much lower than the given quantization level is capable of representing. In terms of representing information content, an image's typically low information content results in unused capacity, i.e., extra bits beyond those required for the given information content. Data compression has as one of its objectives adaptively matching a minimal length codeword to particular information content, to thereby minimize unused capacity. In general, this involves converting the original data into another form of digital representation, which then reduces the total data rate significantly because the length of the codewords, i.e., the number of bits per codeword, adaptively tracks the information content.

The prior art has exploited information correlation among multi-source data sets, i.e., multispectral data, mainly by using lossy encoding techniques which involve a complicated transformation of the data into a different domain. A simple data information content prediction scheme using a data set from a neighboring spectral band has not performed well.

The prior art has attempted to use a distortionless pre-coding scheme involving a simple single subtraction of corresponding members of a second original data set from a first original data set. As shown in FIG. 2, data set 1 (a_0, a_1, a_2, a_3), item 10, is subtracted from data set 2 (b_0, b_1, b_2, b_3), item 10, to form what is referred to as a cross-delta data set. Prediction using such a cross-delta data set has not significantly enhanced compression efficiency because, for example, the material under observation exhibits significantly different spectral properties among the original data sets, respectively, or because the material under observation has undergone a significant change during the time elapsed between the sampling that produced the first data set and the sampling that produced the second data set, despite the data sets sharing the same frequency spectrum.

As an alternative, as shown in FIG. 3, the prior art has attempted to employ a simple single adjacent data precoding technique in which adjacent members within each single data set 10 and 12 are subtracted from one another to produce what is referred to as an adjacent-delta data set,

respectively. FIG. 4 depicts a plot of the distribution of delta values for either the cross-delta or adjacent-delta technique, taken alone.

The known multi-source encoding scheme applies a Karhunen-Loeve transform to data from each source, followed by further processing and encoding. This technique is inherently lossy because of the precision required in computing the transforms. Also, the procedure suffers the problem that it requires a tremendous amount of computation.

Accordingly, a need exists for a simple method that improves data compression efficiency by exploiting information correlation among multi-source, or time-shifted, data sets.

SUMMARY OF THE INVENTION

It is an object of the present application, therefor, to improve data compression.

It is a further object to improve data compression efficiency by exploiting information correlation among multi-source, or time-shifted single source, data sets.

These and other objects of the present invention are fulfilled by providing a pre-compression-coding method and device that produce a double-difference data set, i.e., an adjacent-delta calculation performed on two cross-delta data sets or a cross-delta calculation performed on two adjacent-delta data sets on one of (1) two adjacent spectral bands coming from two discrete sources, respectively, and (2) two time-shifted data sets from a single source. The resulting double-difference set is then coded using either a distortion-less data encoding scheme (entropy encoding) or a lossy data compression scheme.

Further, these and other objects of the present application are fulfilled by providing a method and device for reconstructing a second original data set, the second original data set having been represented by a double-difference data set due to a double difference calculation upon the second original data set and a first original data set.

The foregoing and other objectives of the present invention will become more apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not limitative of the present invention, and wherein:

FIG. 1 depicts a typical distribution of intensity values for pixels represented by an 8-bit word;

FIG. 2 depicts a cross-delta single difference calculation;

FIG. 3 depicts an adjacent-delta single difference calculation;

FIG. 4 depicts a typical distribution of delta-values for pixels represented by an 8-bit word when only a single difference pre-coding scheme is used;

FIG. 5 depicts a more narrow distribution of delta-values for representation of a pixel by an 8-bit word that results when the double-difference pre-coding method of the present application is applied;

FIG. 6 depicts a double-difference calculation in the form of a cross-delta calculation performed on two discrete adjacent-delta data sets;

FIG. 7 is an alternative depiction of the double-difference calculation shown in FIG. 6;

FIG. 8 depicts a reconstruction calculation, i.e., the inverse calculation to the double-difference calculation depicted in FIG. 6.

FIG. 9 is an alternative depiction of the reconstruction calculation shown in FIG. 8;

FIG. 10 depicts a double-difference calculation in the form of an adjacent-delta calculation performed on a cross-delta data set;

FIG. 11 is an alternative depiction of the double-difference calculation of FIG. 10;

FIG. 12 is a reconstruction calculation, i.e., the inverse calculation to the double-difference calculation depicted in FIG. 10;

FIG. 13 is an alternative depiction of the reconstruction calculation shown in FIG. 12.

FIG. 14 is a depiction of the double-difference calculation according to the present invention for three or more data sources;

FIG. 15 is the inverse or reconstruction calculation to the at-least-three data source pre-coding double-difference calculation depicted in FIG. 14;

FIG. 16 depicts the preferred hardware embodiment for the double-difference calculator of the present invention;

FIG. 17 depicts the preferred hardware embodiment for the reconstruction calculator of the present invention;

FIG. 18 depicts an alternative hardware embodiment for the double-difference calculator of the present application;

FIG. 19 depicts an alternative hardware embodiment of the reconstruction calculator of the present invention;

FIG. 20 depicts a programmed computer embodiment of the double-difference calculator of the present application; and

FIG. 21 depicts a programmed computer embodiment of the reconstruction calculator of the present application.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The preferred embodiments of the present application improve data compression performance by a pre-compression-coding scheme that produces a double-difference data set, this double-difference set being the object of subsequent compression.

Referring now to the drawings, FIG. 6 depicts a first type of double-difference calculation in which an adjacent-delta set data is formed for each of original data sets 10 and 12 by subtracting adjacent members of the data set from each other, respectively. Then, a cross-delta data set is formed by subtracting corresponding members of the first adjacent-delta data set from the second adjacent-delta data set to produce a cross-delta data set, i.e., the double-difference data set.

In more detail regarding FIG. 6, the adjacent-delta value for members zero and one of set 1,

$$\Delta_{A1}^{1,0} = 3 = a_1 - a_0 = 102 - 99.$$

Similarly,

$$\Delta^{2,1}_{A1} = -4 = 98 - 104 \text{ and } \Delta^{3,2}_{A1} = 2 = 100 - 98.$$

For the adjacent delta value for members zero and one of set 2,

$$\Delta^{1,0}_{A2} = 5 = b_1 - b_0 = 101 - 96.$$

Similarly,

$$\Delta^{2,1}_{A2} = -4 = 97 - 101 \text{ and } \Delta^{3,2}_{A2} = 2 = 99 - 97.$$

For the cross-delta value for the zeroth corresponding members of the adjacent-delta data sets,

$$\Delta^{O}_{X} = 2 = \Delta^{1,0}_{A2} - \Delta^{1,0}_{A1} = 5 - 3.$$

Similarly,

$$\Delta^{1}_{X} = 0 = -4 - (-4) \text{ and } \Delta^{2}_{X} = 0 = 2 - 2.$$

FIG. 7 depicts a block diagram of the double-difference calculation of FIG. 6. Hereafter, the differencing operation will also be referred to as Differential Pulse Code Modulation, as performed by a Differential Pulse Code Modulator (DPCM) with a linear quantizer. A DPCM 14 receives N-bits per word data from source 1 and outputs N+1 bit data to a DPCM 18. The DPCM 14 and 16 each produce an adjacent-delta data set. Another DPCM 16 receives N-bit data from source 2 and outputs N+1 bit data to the DPCM 18. The DPCM 18 produces an N+2 bits per word cross-delta data set therefrom and outputs it as a double-difference data set to a distortionless or lossy data encoder 20, which then outputs encoded, i.e., compressed, data from source 2. For an inputted original data set formed of N-bit words, the DPCM processor will produce (N+1) bit words having both positive and negative values, hence the need for an additional bit.

The function of the preferred embodiments is to compute a double-difference between original data sets taken from distinct sources or original data sets taken from a single source, albeit sampled at different points in time (time-shifted). The DPCM is basically a prediction device that results in a prediction error. For example, for two adjacent data sources producing two adjacent spectral bands (neighboring bands in the frequency spectrum), an adjacent-delta data set made from a first one of the original data sets is used as a predictor for the adjacent-delta data sets in the other original data set. The prediction error is then coded using either a distortionless or lossy compression scheme, such compression schemes may require that the input data values be non-negative integers. In such a circumstance, a signal conditioning procedure that adds a value of 2N+1 −1 to all data values to be compressed can be included.

This prediction scheme is based on the observation that in any data set, information resides at the point where changes occur, i.e., at an edge. No information exists if all members of the data set are of the same value, i.e., where there are no edges. The DPCM 14, FIG. 7, effectively removes any background shifts and retains the edge (change) information in the data set from a particular data source.

When material under observation produces different original data sets for different data sources (such as multiple

spectral bands), it is likely that the change in edge information is smaller across spectral bands (i.e., between neighboring bands) than within a particular spectral band. This smaller change in edge information provides the improvement in cross-spectral band data compression over the prior art single spectral band compression. The DPCM 18 reveals such smaller changes in its output.

FIG. 8 depicts a reconstruction calculation, i.e., the inverse calculation to the double-difference calculation depicted in FIG. 6, that reconstructs the second original data set. Certain information is stored after the double difference calculation of FIG. 6 is completed: (1) the double-different data set {Δ_x}; (2) the zeroth member of the second original data set, bo; and (3) either the adjacent delta data set for the first original data set, {$\Delta A1$}, or the first original data set itself {a}.

In more detail regarding FIG. 8, first the adjacent-delta value for the members zero and one of the second original data set

$$\Delta^{1,0}_{A2},$$

is recovered by adding the corresponding members of the first adjacent-delta data set {$\Delta A1$}, and the double different data set {Δx}, such that

$$\Delta^{1,0}_{A2} = 5 = 3 + 2 = \Delta^{1,0}_{A1} + \Delta^{o}_{x}.$$

Similarly,

$$\Delta^{2,1}_{A2} = -4 = -4 + 0 \text{ and } \Delta^{3,2}_{A2} = 2 = 2 + 0.$$

Next, the members of the second original data set {b} are reconstructed recursively using bo as an initial value. Member b1 is formed from adding bo to

$$\Delta^{1,0}_{A2}$$

such that b1=101=96+5=bo to

$$\Delta^{1,0}_{A2}.$$

Next, b2 is formed from adding b1 to

$$\Delta^{2,1}_{A2}$$

such that

$$b2 = 97 = 101 + (-4) = b1 + \Delta^{2,1}_{A2}.$$

Similarly,

$$b3 = 99 = 97 + 2 = b2 + \Delta^{3,2}_{A2}.$$

Note that if the first original data set is stored rather than the first adjacent-delta data set, then the first adjacent delta data set must be determined from the first original data set prior to starting the reconstruction calculation.

FIG. 9 depicts in block diagram form the decoding necessary to retrieve information produced by the double-

difference operation shown in FIG. 6, i.e., it is an alternative depiction of FIG. 8. The DPCM 22 receives N-bits per word data from source 1 and outputs N+1 bits per word data to an inverse DPCM 26. A distortionless or lossy data encoder 24 receives compressed data from source 2 and outputs N+2 bits per word data to the inverse DPCM 26, which outputs an N+1 bits per word signal to another inverse DPCM 28 (whose N bits per word output is the decoded data from source 2). The pre-processed band 1 data is used as an external reference input to the inverse DPCM 26. The inverse DPCM 28 requires that the first data value of band 2 be available, this first data value having been saved in the encoded data file in an appropriate format. Comparing FIG. 9 with FIG. 7, the output of the inverse DPCM 26 has the same value as the output of the DPCM 16. Item 28 executes the inverse of the process executed by item 16.

A second and more preferred double-difference calculation is depicted in FIG. 10. FIG. 10 shows the double-difference set being formed from, first, a cross-delta data set prepared by subtracting corresponding members of a second data set 12 from a first data set 10. Second, an adjacent-delta data set is formed by subtracting adjacent members of the cross-delta data set.

In more detail regarding FIG. 10, for the cross-delta value produced from corresponding zeroth members of the first and second original data sets, ao and bo,

$$\Delta_x^o = -3 = bo - ao = 96 - 99.$$

Similarly,

$$\Delta_x^1 = -1 = 101 - 102, \Delta_x^2 = -1 = 97 - 98, \text{ and } \Delta_x^3 = -1 = 99 - 100.$$

Next, for the adjacent-delta value for the members zero and one of the cross-delta data set,

$$\Delta_A^{1,0} = 2 = \Delta_x^1 - \Delta_x^o = -1 - (-3).$$

Similarly,

$$\Delta_A^{2,1} = 0 = -1 - (-1) \text{ and } \Delta_A^{3,2} = 0 = -1 - (-1).$$

FIG. 11 depicts a block diagram representation of the double-difference calculation shown in FIG. 10. A DPCM 30 receives N-bits per word data from each of sources 1 and 2, respectively, and outputs N+1 bits per word data to an adjacent DPCM 32. The DPCM 30 produces a cross-delta data set. A DPCM 32 produces an N+2 bits per word adjacent-delta data set therefrom and outputs it as the double-difference data set to either a distortionless or lossy data encoder 34, which outputs the compressed source data. FIG. 11 has the advantage over FIG. 7 in that it requires only a single DPCM for the adjacent-delta data set preparation phase.

FIG. 11 and FIG. 7 produce equivalent results by relating the encoder input data samples and the input source data in the figures, respectively. Let a0, a1, . . . and b0, b1, b2, ... be original data sets from source 1 and 2, respectively. The first level of DPCM (i.e., DPCM's 14 and 16) in FIG. 7 will produce, respectively, the values of

(a1–a0), (a2–a1), (a3–a2), . . . for source 1   (1)

(b1–b0), (b2–b1), (b3–b2), . . . for source 2   (2)

The second level of DPCM in FIG. 7 (i.e., DPCM 18) will produce the data sequence to be coded by the following data coder:

(b1–b0)–(a1–a0), (b2–b1)–(a2–a1), (b3–b2)–(a3–a2), . . .   (3)

The data sequence can be written as

(b1–a1)–(b0–a0), (b2–a2)–(b1–a1), (b3–a3)–(b2–a2), . . .   (4)

which can also be obtained by the DPCM 30 first taking the difference of data from sources 1 and 2 (to produce a cross-delta data set), as FIG. 11 depicts, to give:

(b0–a0), (b1–a1), (b2–a2), . . .   (5)

followed by the DPCM 32 operating on a previous data value from this cross-delta data set, or data sequence to produce an adjacent-delta data set.

FIG. 12 depicts a reconstruction calculation, i.e., the inverse calculation to the double-difference calculation depicted in FIG. 10, that reconstructs the second original data set. Certain information is stored after the double difference calculation of FIG. 10 is completed: (1) the double-difference data set, $\{\Delta A\}$; (2) the zeroth member of the cross-delta data set,

$$\Delta_x^o;$$

and (3) the first original data set, $\{a\}$.

In more detail regarding FIG. 12, the members of the cross-delta data set $\{\Delta x\}$ are recovered recursively using the zeroth member of the cross-delta data set,

$$\Delta_x^o,$$

as an initial value. Member

$$\Delta_x^1$$

is formed by adding

$$\Delta_x^o \text{ to } \Delta_A^{1,0}$$

such that

$$\Delta_x^1 = -1 = \Delta_x^o + \Delta_A^{1,0} = -3 + 2.$$

Next,

$$\Delta_x^2$$

is formed by adding

$$\Delta_x^1 \text{ to } \Delta_A^{2,1}$$

such that

$$\Delta_x^2 = -1 = \Delta_x^1 + \Delta_A^{2,1} = -1 + 0.$$

Similarly,

$$\Delta_x^3 = -1 = \Delta_x^2 + \Delta_A^{3,2} = -1 + 0.$$

Next, the members of the second original data set are $\{b\}$ are reconstructed by adding corresponding members of the cross-delta data set, $\{\Delta_x\}$, and the first original data set, $\{a\}$, respectively, such that

$$b_1 = 101 = -1 + 102 = \Delta_x^1 + a_1,$$
$$b_2 = 97 = -1 + 98 = \Delta_x^2 + a_2, \text{ and}$$
$$b_3 = 99 = -1 + 100 = \Delta_x^3 + a_3.$$

FIG. 13 depicts the decoding scheme for use with the double-difference data produced by FIG. 10, i.e., it is an alternative depiction of FIG. 12. FIG. 13 produces an equivalent result to that produced by FIG. 9. A distortionless or lossy data decoder 36 receives encoded source 2 data and

outputs a signal to a first inverse DPCM **38** which outputs a signal to a second inverse DPCM **40**. N-bit data from source **1** is also input to the inverse DPCM **40**, which then outputs decoded source **2** data.

A variety of distortionless source encoding/decoding techniques can be employed for the entropy coder/decoder. One that works particularly well on imaging and science data is the Rice algorithm (R. F. Rice, "Some practical universal noiseless coding techniques," JPL pub. 79–22, 1979, hereby incorporated by reference). This algorithm has pre-processing and entropy coding. The pre-processing performs data prediction on N-bit input data samples and mapping that maps the (N+1)-bit data samples back to all non-negative N-bit data. The entropy coding itself is a collection of discrete Huffman codings, each optimal for a particular entropy range. It adapts to the data information rate by selecting the Huffman code option that gives the shortest codeword length for an input sample block of a fixed number of samples, such as 8 or 16. If the Rice algorithm is used to implement the data encoding, one can make use of the DPCM pre-processing in the algorithm as, for example, the second stage DPCM **32** in FIG. **11**. Such implementation would then only require a DPCM as an external pre-processor.

For encoding and decoding more than two sources, an architecture which builds on the basic block diagram in FIG. **11** can be used. One data source, such as spectral band **1**, should be compressed without cross-band information and the other bands will use an adjacent band as a reference in the DPCM pre-processing. This architecture for up to 4 data sources is given in FIGS. **14** and **15** (the associated inverse technique).

The preferred hardware embodiment of the preferred type of double-difference calculation (cross-adjacent) is depicted in FIG. **16**. An arithmetic complement device **88** receives data from source **1** and outputs the complement thereof to adder **90**, which also receives data from source **2**. The adder **90** outputs its sum, i.e., a cross-delta data set, to an adder **96** and a one-sample delay circuit **92**, which outputs the delayed cross-delta data set to an arithmetic complement device **94**. The complement device **94** outputs the complement of the delayed cross-delta data set to the adder **96**, and the adder **96** outputs an adjacent-delta, i.e., double-difference data set. FIG. **16** is drawn with the assumption that the discrete electronic structures introduce no significant delay by their operation, hence the delay circuit **92** has been included.

The complement device **88** and the adder **90** represent a first stage DPCM processor while the one sample delay buffer **92**, the complement device **94**, and the adder **96** represent a second DPCM processor stage. The first DPCM processor stage has two data inputs, one being used as a reference input. The input data can be in 1's or 2's complement arithmetic integer numbers.

FIG. **17** depicts the preferred hardware embodiment for the reconstruction calculator of the present invention corresponding to the reconstruction calculation depicted in FIG. **12**. In decoding, the inverse DPCM processor is implemented using the same logic in the encoder except that the complement circuit is no longer needed. A first adder **89** receives the stored preprocessed data from source **2**, i.e., the cross-adjacent double difference data set. The output of the adder **89** is connected to a one sample delay circuit **91** and a second adder **93**. The one-sample delay circuit **91** delays the output of the adder **89** and inputs it back into the adder **89**. The adder **93** also receives the original data set from source **1**, uses it as a reference, and outputs the reconstructed second original data set. FIG. **17** is drawn with the assump-

tion that the discrete electronic structures introduce no significant delay by their operation, hence the delay circuit **91** has been included.

A hardware embodiment for the second preferred double-difference calculation, adjacent-cross, is shown in FIG. **18**. A one sample delay circuit **98** receives data from source **1** and outputs the delayed original sourced data to the complementer **100**. The complementer **100** outputs a signal to an adder **102**. The adder **102** also receives the original data from source **1** and outputs an adjacent-delta data set to another complementer **112**. A second one-sample delay circuit **106** receives data from source **2** and outputs the delayed original source **2** data to a complementer **108**. The complementer **108** outputs a signal to a second adder **110**. The adder **110** also receives the original source **2** data and outputs an adjacent-delta data set to a third adder **114**. The third adder **114** also receives a signal from the complementer **112** and outputs a cross-delta double-difference data set. FIG. **18** is drawn under the assumption, discussed above, that any significant delays must be indicated, hence the inclusion of the delay circuits **98** and **106**.

FIG. **19** depicts an alternative hardware embodiment of the reconstruction calculator of the present invention corresponding to the calculation depicted in FIG. **8**. The stored preprocessed, i.e., adjacent-cross double difference, data is input to an adder **122**. The stored original data from source **1** is passed through a DPCM **124** (see FIG. **18** items **98**, **100**, and **102** for a discrete hardware equivalent thereof). A one sample delay circuit delays the output of the adder **122** and inputs it back into the adder **122**. In addition, the adder **122** receives a signal from the DPCM **124**. Again, FIG. **19** is drawn under the assumption, discussed above, that any significant delays must be indicated, hence the inclusion of the delay circuit **126**.

The discrete electronic structures shown in FIGS. **16–19** can be realized with well-known analog or digital hardware components using either custom or standard practice design methodologies or can be implemented on a single integrated circuit. For lossless data encoding implementation of the double-difference data sets, the data compression hardware is well known and readily available. The embodiments of the present application can be implemented as an additional module in lossless data compression hardware, and thereby be incorporated in lossless data compression chips.

FIG. **20** depicts a further hardware embodiment of either of the double-difference methods discussed above. A programmed computer **118** receives data from a data source **116** and different data from a data source **120** and outputs a double-difference data set. As supported by the discussion above, the first data source **116** could be a piece of hardware discrete from the second data source **120**, or it could represent the same single piece of hardware that produced a first and second original data set at different points in time, respectively. Based upon the discussion above, one of ordinary skill in the art could write a program to implement the double-difference calculation without enduring undue experimentation for the sake of brevity, further discussion of this point is omitted.

FIG. **21** depicts a further hardware embodiment of either of the reconstruction calculations discussed above. A programmed computer **128**: receives a first original data set (or its corresponding first adjacent-delta data set) from memory **130**; receives a double difference data set from memory **132**; and optionally receives an $(i-1)^{th}$ member of the second original data set (i.e., the one to be reconstructed) from memory **134**, depending on the type of reconstruction being performed. Again, given the ordinary level of skill in the art, further discussion on this point is omitted.

In contrast to the prior art, as depicted for example in FIG. 5, the presently disclosed double-difference methods produce delta-value distributions that are not widely dispersed. This is reflected in the result that such double-difference data sets achieve compression ratios exceeding those that can be achieved using only a single set of original data.

The present invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

I claim the following:

1. A pre-coding method to improve data compression performance by removing correlation between a first original data set and a second original data set each having M members, respectively, comprising:

(a) determining a difference between one of (1) adjacent members in each of the first and second original data sets to form a first adjacent-delta data set and a second adjacent-delta data set, respectively, and (2) corresponding members of the first original set and the second original sets, respectively, to form a first cross-delta data set; and

(b) determining a second difference between one of (3) corresponding members of the first adjacent-delta data set and the second adjacent-delta data sets, respectively, to form a cross-delta data set, and (4) adjacent members in the first cross-delta data set, to form an adjacent-delta data set;

wherein step (a), if the first difference is taken as type (1), then in step (b) the second difference is taken as type (3); and

wherein step (a), if the first difference is taken as type (2), then in step (b) the second difference is taken as type (4);

a result of the step (b) being a compression-efficiency-enhancing, double-difference data set, for subsequent compression coding.

2. A method as in claim 1, wherein:

the first and second original data sets have N-bits per member, respectively;

the first and second adjacent-delta data sets have N+1 bits per member; and

the double-difference set has N+2 bits per member.

3. A method as in claim 1, wherein:

the first original data set is sampled from a source at a different time than the second original data set is sampled from the same source.

4. A method as in claim 1, wherein:

the first original data set is from a first data source and the second original data set is from a second data source discrete from the first source.

5. A method as in claim 1, wherein:

the first data source operates in a first spectral band, the second data source operates in a second spectral band, and the first and second spectral bands are adjacent.

6. A method as in claim 1, wherein:

information content is significantly redundant between the first original data set and the second original data set.

7. A method as in claim 1, wherein:

the first and second original data sets are image data.

8. A pre-coding apparatus to improve data compression performance by removing correlation between a first original

nal data set and a second original data set each having M members, respectively, comprising:

first means for determining a first difference between one of (1) adjacent members in each of the first and second original data sets to form a first adjacent-delta data set and a second adjacent-delta data set, respectively, and (2) corresponding members of the first original set and the second original sets, respectively, to form a first cross-delta data set; and

second means, responsive to the first means, for determining a second difference between one of (3) corresponding members of the first adjacent-delta data set and the second adjacent-delta data sets, respectively, to form a cross-delta data set, and (4) adjacent members in the first cross-delta data set, to form an adjacent-delta data set;

wherein if the first difference from the first means is type (1), then the second difference from the second means is type (3); and

wherein if the first difference from the first means is type (2), then the second difference from the second means is type (4);

output of the second means being a compression-efficiency-enhancing, double-difference data set, for subsequent compression coding.

9. An apparatus as in claim 8, wherein:

the first and second original data sets have N-bits per member, respectively;

the first and second adjacent-delta data sets have N+1 bits per member; and

the double-difference set has N+2 bits per member.

10. An apparatus as in claim 8, wherein:

the first original data set is sampled from a source at a different time than the second original data set is sampled from the same source.

11. An apparatus as in claim 8, wherein:

the first original data set is from a first data source and the second original data set is from a second data source.

12. An apparatus as in claim 8, wherein:

the first data source operates in a first spectral band, the second data source operates in a second spectral band, and the first and second spectral bands are adjacent.

13. An apparatus as in claim 8, wherein:

information content is significantly redundant between the first original data set and the second original data set.

14. An apparatus as in claim 8, wherein:

the first and second original data sets are image data.

15. A method for reconstructing a second original data set, the second original data set having been represented by an adjacent-cross double difference data set due to a double difference calculation upon the second original data set and a first original data set,

an adjacent-cross double difference data set and an ith member of the second original data set having been stored, and a first adjacent-delta data set associated with the first original data having been preset,

the method comprising:

(a) retrieving the first adjacent-delta data set and the adjacent-cross double difference data set;

(b) summing, after step (a), corresponding members of the first adjacent-delta data set and the adjacent-cross double difference data set, respectively, to form a second adjacent-delta data set associated with the second original data set;

(c) retrieving the ith member of the second original data set;

(d) setting, after step (c), an initial value equal to the ith member of the second original data set; and

(e) restoring recursively, after steps (b) and (d), members of the second original data set as a function of the initial value and the second adjacent-delta data set.

16. A method as in claim 15, wherein:

the first and second original data sets have N-bit members, respectively; and

the first and second adjacent-delta sets have N+1 bits per member; and

the double-difference set has N+2 bits per member.

17. A method as in claim 15, wherein:

the first original data set is sampled from a source at a different time than the second original data set is sampled from the same source.

18. A method as in claim 15, wherein:

the first original data set is from a first data source and the second original data set is from a second data source discrete from the first source.

19. A method as in claim 15, wherein:

the first data source operates in a first spectral band, the second data source operates in a second spectral band, and the first and second spectral bands are adjacent.

20. A method as in claim 15, wherein:

information content is significantly redundant between the first original data set and the second original data set.

21. A method as in claim 15, wherein:

the first and second original data sets are image data.

22. A method a in claim 15, wherein:

the first original data set is stored prior to executing the method;

the first adjacent-delta data set being preset by determining a difference between adjacent members in the first original data set to form the first adjacent-delta data set.

23. An apparatus for reconstructing a second original data set, the second original data set having been represented by an adjacent-cross double difference data set due to a double difference calculation upon the second original data set and a first original data set, the apparatus comprising:

a first memory for storing an adjacent-cross double difference data set;

a second memory for storing an ith member of the second original data set;

preset means for presetting a first adjacent-delta data set associated with the first original data;

summation means, responsive to the first memory and the preset means, for summing corresponding members of the first adjacent-delta data set and the adjacent-cross double difference data set, respectively, to form a second adjacent-delta data set associated with the second original data set;

initialization means, responsive to the second memory, for setting an initial value equal to the ith member of the second original data set;

restoration means, responsive to the initialization means and the summation means, for restoring recursively the second original data set as a function of the initial value and the second adjacent-delta data set.

24. An apparatus as in claim 23, wherein:

the first and second original data sets have N-bit members, respectively; and

the first and second adjacent-delta sets and the double-difference set have N+1 bits, respectively.

25. An apparatus as in claim 23, wherein:

the first original data set is sampled from a source at a different time than the second original data set is sampled from the same source.

26. An apparatus as in claim 23, wherein:

the first original data set is from a first data source and the second original data set is from a second data source.

27. An apparatus as in claim 23, wherein:

the first data source operates in a first spectral band, the second data source operates in a second spectral band, and the first and second spectral bands are adjacent.

28. An apparatus as in claim 23, wherein:

information content is significantly redundant between the first original data set and the second original data set.

29. An apparatus as in claim 23, wherein:

the first and second original data sets are image data.

30. An apparatus as in claim 23, wherein the preset means includes:

a third memory for storing the first original data set; and

difference means, responsive to the third memory, for determining a difference adjacent members in the first original data set to form the first adjacent-delta data set.

31. A method for reconstructing a second original data set, the second original data set having been represented by a cross-adjacent double difference data set due to a double difference calculation upon the second original data set and a first original data set,

an ith member of a cross-delta data set, a first original data set, and the cross-adjacent double difference data set having been stored,

the method comprising:

(a) retrieving the ith member of the cross-delta data set;

(b) setting, after step (a), an initial value equal to the ith member of the cross-delta data set;

(c) restoring recursively, after step (b), the cross-delta data set as a function of the initial value and the cross-adjacent double difference data set;

(d) retrieving the first original data set; and

(e) restoring, after steps (c) and (d), members of the second original data set by summing corresponding members of the first original data set and the cross-delta data set, respectively.

32. A method as in claim 31, wherein:

the first and second original data sets have N-bit members, respectively; and

the first and second adjacent-delta sets have N+1 bits per member; and

the double-difference set has N+2 bits per member.

33. A method as in claim 31, wherein:

the first original data set is sampled from a source at a different time than the second original data set is sampled from the same source.

34. A method as in claim 31, wherein:

the first original data set is from a first data source and the second original data set is from a second data source discrete from the first source.

35. A method as in claim 31, wherein:

the first data source operates in a first spectral band, the second data source operates in a second spectral band, and the first and second spectral bands are adjacent.

36. A method as in claim 31, wherein:

information content is significantly redundant between the first original data set and the second original data set.

37. A method as in claim 31, wherein:

the first and second original data sets are image data.

38. An apparatus for reconstructing a second original data set, the second original data set having been represented by a cross-adjacent double difference data set due to a double difference calculation upon the second original data set and a first original data set, the apparatus comprising:

a first memory storing an ith member of a cross-delta data set;

a second memory storing the cross-adjacent double difference data set;

a third memory storing a first original data set;

initialization means, responsive to the first memory, for setting an initial value equal to the ith member of the cross-delta data set;

restoration means, responsive to the initialization means and the second memory, for restoring recursively the cross-delta data set as a function of the initial value and the cross-adjacent double difference data set;

summation means, responsive to the restoration means and the third memory, for restoring members of the second original data set by summing corresponding members of the first original data set and the cross-delta data set, respectively.

39. An apparatus as in claim 38, wherein:

the first and second original data sets have N-bit members, respectively; and

the first and second adjacent-delta sets have N+1 bits per member; and

the double-difference set has N+2 bits per member.

40. An apparatus as in claim 38, wherein:

the first original data set is sampled from a source at a different time than the second original data set is sampled from the same source.

41. An apparatus as in claim 38, wherein:

the first original data set is from a first data source and the second original data set is from a second data source discrete from the first source.

42. An apparatus as in claim 38 wherein:

the first data source operates in a first spectral band, the second data source operates in a second spectral band, and the first and second spectral bands are adjacent.

43. An apparatus as in claim 38, wherein:

information content is significantly redundant between the first original data set and the second original data set.

44. An apparatus as in claim 38, wherein:

the first and second original data sets are image data.

*   *   *   *   *